

**LSU Dept. of Physics and Astronomy**  
**Qualifying Exam**  
**Thermo and Statistical Mechanics Question Bank**  
(05/2023)

1. This question has two independent parts:  
(a) Show that the enthalpy  $H$  can be related to the Gibbs's free energy as

$$H = -T^2 \left[ \frac{\partial}{\partial T} \left( \frac{G}{T} \right)_P \right]$$

- (b) Show that

$$C_V = -T \left( \frac{\partial^2 F}{\partial T^2} \right)_V$$

2. Mercury has a radius of  $2.44 \times 10^6$  m and is at a distance of  $5.8 \times 10^{10}$  m from the Sun which has a radius of  $7 \times 10^8$  m. The power output from the Sun is  $4 \times 10^{26}$  W. Note that one side of Mercury always faces the Sun. Treating Mercury as a black body:

- (a) Find the total power absorbed by Mercury from the Sun. (2 pts)
- (b) If Mercury is in thermodynamic equilibrium, it will emit the same total power as it receives from the Sun. Assuming that the temperature of the "hot side" of Mercury is uniform, find this temperature. (4 pts)
- (c) What is the ratio of peak frequency of the radiation emitted by the Sun to that of Mercury? (4 pts)

3. A box of volume  $V$  has three partitions filled with ideal gases with initial temperature  $T = 300$  K and pressure  $P = 2$  atm. In the first partition there is a kilomole of helium gas, in the second there are two kilomoles of neon gas, and three kilomoles of argon gas are in the third partition. After the partitions are removed and the gases diffuse after sometime in the entire box,
- (a) Find the final individual pressures of each component and the total pressure. (3 pts)
- (b) Find the change in Gibbs free energy  $G$  in the mixing process. (3 pts)

(c) Find the change in entropy of the system in the mixing process. (4 pts)

4. This question has two independent parts:

(a) Show that the internal energy  $U$  can be related to the Helmholtz function  $F$  as

$$U = -T^2 \left[ \frac{\partial}{\partial T} \left( \frac{F}{T} \right)_V \right]$$

(b) Show that

$$C_P = -T \left( \frac{\partial^2 G}{\partial T^2} \right)_P$$

5. This question has two independent parts:

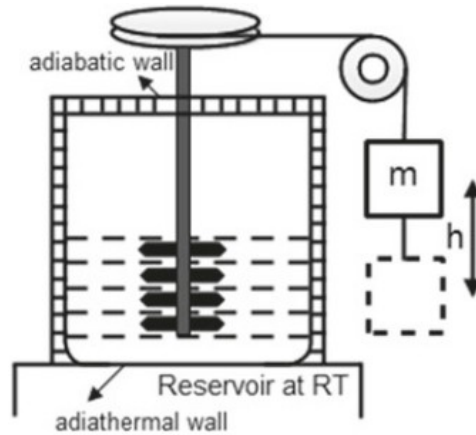
(a) Find the melting point of Aluminum at a pressure of  $10^7$  Pa if at atmospheric pressure ( $10^5$  Pa) it melts at 550 K. Note that while it melts its density decreases from  $3 \times 10^3$  kg/m<sup>3</sup> to  $2.9 \times 10^3$  kg/m<sup>3</sup>. Latent heat of fusion of aluminium is  $24 \times 10^3$  J/kg.

(b) The internal energy of a system at a fixed volume is found to depend on the temperature  $T$  as  $E(T) = aT^2 + bT^4$ , where  $a$  and  $b$  are constants. Find the expression of entropy.

6. In Fig. 1, a liquid is in contact with a reservoir at room temperature  $T$ . When the object of mass  $m$  falls through a height  $h$ , the paddle inside the liquid moves and this causes an increase in the temperature of the liquid. The adiathermal contact between the system and the reservoir causes the heat flow from the former to the latter, as a result, the state of system is not affected.

Giving detailed explanations, find

- (a) the change in entropy of water
- (b) the change in entropy of paddle
- (c) the change in entropy of mass  $m$
- (d) the change in entropy of the reservoir.



**Figure 1:** Figure shows a Joule paddle. RT refers to room temperature.

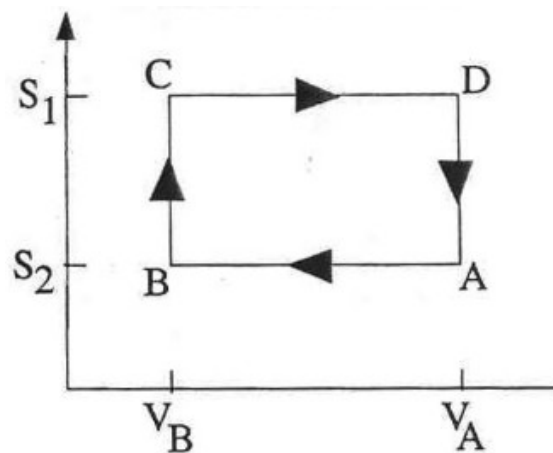
7. (a) If  $n$  mole of an ideal gas expands isothermally and reversibly to twice its original volume. Calculate the change in entropy of the gas, and of the universe. What happens if the gas undergoes free expansion?

(b) The specific volume of a liquid is much less than that of its vapors. If we assume that the vapor obeys the equation for an ideal gas show that pressure depends exponentially on temperature.

8. (a) A cylinder which is thermally insulated from the environment contains a mole of ideal gas with constant heat capacity  $C_V$ . The cylinder has a piston which can vertically without friction. Pressure  $P_1$  is applied to the piston, and then the pressure is changed abruptly to  $P_2$ . As a result, the gas volume changes adiabatically. Find the temperature  $T_2$  and the volume  $V_2$  after the thermodynamic equilibrium has been reached.

(b) After the thermodynamic equilibrium has been established in above part, if the pressure is abruptly reset to its original value  $P_1$  find the final values of the temperature  $T_f$  and the volume  $V_f$  once the thermodynamic equilibrium is established again. Use the first law of thermodynamics and the adiabatic equation to compute the difference in temperatures ( $T_f - T_1$ ). Discuss the sign and the relative magnitude of the temperature difference with respect to the change in pressure.

9. 1000 joules of heat are added at constant pressure of 1 atm to an ideal monoatomic gas. The system expands in the process and its temperature rises 10 K.
- (a) Find the number of moles present (2 pts).
- (b) Find the increase in volume (3 pts).
- (c) Find the entropy change in terms of the initial temperature (5 pts).



**Figure 2:** Figure shows the Otto cycle. Gas is compressed adiabatically in  $A \rightarrow B$ , gas is heated isochorically in  $B \rightarrow C$ , gas is expanded adiabatically in  $C \rightarrow D$ , and gas is cooled isochorically in  $D \rightarrow A$ .

10. Figure 2 depicts the approximate behavior of a gasoline engine which is similar to that of the Otto cycle. Compute the efficiency for an ideal gas (with temperature-independent heat capacities) as a function of the compression ratio  $V_A/V_B$ , and the heat capacity per particle  $C_V$ .
11. (a) Show that, if the temperature is constant, the pressure of an ideal gas in a uniform gravitational field decreases with height according to the formula
- $$p(z) = p(0)e^{-mgz/k_B T}.$$
- (b) The result from the preceding part assumed that temperature is constant, so that equilibrium is attained by the transfer of heat. Now assume heat is not exchanged to achieve equilibrium, but via an *adiabatic* process that holds the quantity  $pV^\gamma$  constant ( $\gamma$  being the adiabatic index). What is  $p(z)$  for this case?

12. The thermodynamic identity is:

$$dE = T dS - p dV + \mu dN. \quad (1)$$

We obtain the definition of temperature, pressure and chemical potential by holding two of  $(E, S, V, N)$  fixed. For example, by holding  $N$  and  $V$  fixed ( $dN = 0, dV = 0$ ) we get  $1/T = \partial S / \partial E|_{N,V}$ .

- (a) Generalizing this idea, how many formulas of this form can be derived by holding two quantities fixed in Eq. (1)? Derive them all.
- (b) Three of the formulas from part (a) are just the definitions of  $T$ ,  $\mu$  and  $p$ , but the rest of the formulas are nontrivial. Demonstrate that the latter are valid using the triple product rule

$$\left(\frac{\partial x}{\partial y}\right)_z \left(\frac{\partial z}{\partial x}\right)_y \left(\frac{\partial y}{\partial z}\right)_x = -1.$$

13. The internal energy of a thermodynamic system,  $E(S, V, N)$  satisfies the thermodynamic identity

$$dE = T dS - p dV + \mu dN.$$

- (a) Derive the thermodynamic identities for the Helmholtz free energy  $A = E - TS$ , the Gibbs free energy  $G = E + pV - TS$ , and the thermodynamic potential  $\Omega = -A + \mu N$ .
- (b) Using the fact that  $\Omega$  is extensive, show that  $\Omega = pV$ .

14. A steel rod with length  $l = 20$  cm and cross-section  $A = 3$  cm<sup>2</sup> is heated at one end to  $T = 300^\circ\text{C}$ , and touches a block of ice at  $T_i = 0^\circ\text{C}$  with the other end. Assuming that all the heat is transferred along the rod, with no losses through the sides, estimate the mass of ice that melts in  $t = 5$  min. Latent heat of melting for ice is 80 cal/g, the heat conductivity of steel is  $k_t = 0.16$  cal/(s·cm·°C).

15. A monoatomic ideal gas is expanded under such conditions that  $PV^2 = \text{const}$ . What is the heat capacity per mole of the gas under this process?

16. You know the relationship between the entropy,  $S$ , internal energy,  $U$ , number

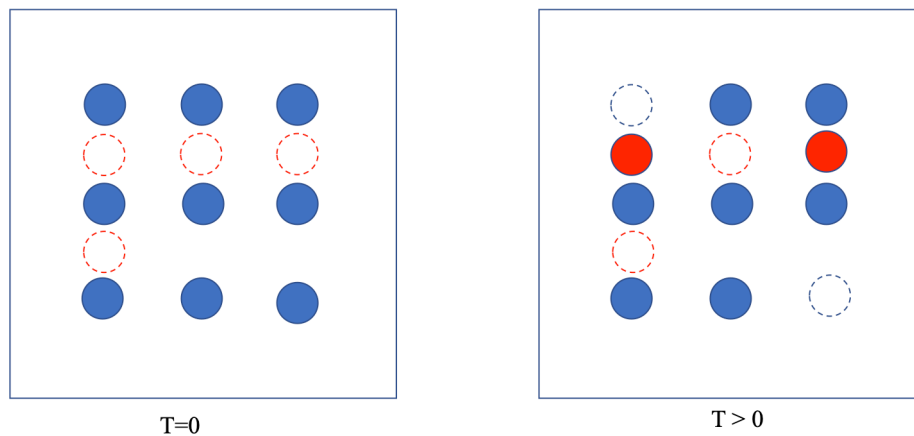
of particles,  $N$ , and volume,  $V$ , of a substance,

$$S = A [UNV]^{1/3},$$

where  $A$  is a constant.

- (a) Verify that entropy is an extensive quantity according to this definition, and obtain the units for the constant  $A$ .
  - (b) Derive the internal energy as a function of temperature, volume, and the number of particles,  $U(N, T, V)$ .
  - (c) Derive the equation of state, i.e. the relationship between pressure,  $P$ , volume, temperature, and the number of particles; Verify that the pressure is an intensive quantity.
  - (d) Derive the heat capacity at constant volume,  $C_v$ .
  - (e) Derive the chemical potential  $\mu(T, P)$ .
17. Consider the following adsorption problem (Fig. 3). A surface has  $N \gg 1$  "best" binding sites, and  $M \gg 1$  "good" binding sites for a particular molecule. Each site can be occupied by at most one molecule. The energy of a molecule at a "good" site is  $\epsilon$  higher than the energy at a "best" site. You initially exposed the surface to a gas of these molecules for a long time at low temperature, so that all  $N$  best sites are occupied by the molecules, and all the good sites are empty, as shown at left. Now you stopped the exposure, and increased the temperature, so that  $n$  molecules may be promoted to "good" sites, while  $N-n$  molecules stay at the "best" sites, as shown at right. The energy of this configuration is obviously  $U = n\epsilon$ .
- (a) For a fixed number of adsorbed molecules the energy is simply determined by the number of molecules at the "best" sites. Write the expression for the degeneracy (multiplicity) of this state, i.e. the state with  $N-n$  molecules at "best" sites, and  $n$  molecules at "good" sites.
  - (b) Using the definition of temperature via the entropy, derive the general equation for  $n$  as a function of temperature. You don't have to solve it yet, but it should only contain  $n$  and known quantities, i.e. be simple and solvable.

- (c) Find  $n(T)$  when there is an equal number of different sites,  $N = M$ . Simplify the final expression as much as you can.
- (d) Show that if  $N \gg M \gg 1$  there are two temperature regimes: low temperature, when the occupation of  $M$ -type sites is low, and high temperature, when this occupation is high. Derive the *approximate and simple* expressions for  $n(T)$  in both limits and roughly estimate the *crossover temperature* between the two regimes. The easiest way to proceed is to look at the general equation you derived, and drop some terms based on physical and mathematical reasoning.



**Figure 3.** Adsorbed atoms on the surface. Left panel: low temperature, all atoms (blue circles) are at “best” sites, while “good” sites are empty (dashed circles). Right panel: higher temperature: atoms shown in red moved from “best” to “good” sites.

18. Consider a system that has four energy eigenstates for single particles: two distinct ones with energy  $E_0$ , and two other distinct levels with energy  $2E_0$ . This system contains 3 non-interacting bosons. What is the temperature range (if any) where we are more likely to find the system in the first excited (net) energy state rather than in the ground state?
19. Consider a system consisting of  $N$  one-dimensional simple-harmonic quantum oscillators at temperature  $T$ . Each oscillator has energy  $E_n = \hbar\omega \left( n + \frac{1}{2} \right)$ , where  $n = 0, 1, 2, \dots$ .
- (a) What is the mean energy of the system?
- (b) Under what conditions does the system obey the equipartition theorem? Explain why.

20. Consider a classical  $N$ -particle system with Hamiltonian

$$H = \sum_{i=1}^N \frac{p_i^2}{2m_i} + \sum_{i=1}^N \frac{k_i}{2} q_i^2,$$

at temperature  $T$ . For this problem, you may use the formulas

$$\int_{-\infty}^{\infty} dx e^{-ax^2} = \frac{\sqrt{\pi}}{\sqrt{a}},$$

$$\int_{-\infty}^{\infty} dx x^2 e^{-ax^2} = \frac{\sqrt{\pi}}{2a^{3/2}}.$$

(a) Show that:

$$\frac{\langle p_i^2 \rangle}{2m_i} = \frac{1}{2} k_B T.$$

(b) Derive a similar relation, involving  $q_i$ .

21. What does a surface of constant energy look like in the phase space of an oscillator of frequency  $\nu$ ? Find the volume  $\Gamma(E)$  of phase space below  $E$  for a classical oscillator of such a frequency. Then find the number of quantum states  $\Omega(E)$  with energy below  $E$  for the same oscillator and show that when  $E$  is large,  $\Gamma/\hbar \approx \Omega$ .

22. (a) For an oscillator with mass  $m$  and angular frequency  $\omega$ , calculate the partition function (i) classically and (ii) quantum mechanically.

(b) With the quantum partition function above, find the internal energy, entropy, and heat capacity of a system of  $N$  such oscillators as a function of temperature  $T$ .

23. An ideal gas consisting of  $N$  particles of mass  $m$  obeying classical statistics is enclosed in a tall cylinder placed in a constant gravitational field, and is in thermal equilibrium. Calculate the classical partition function, Helmholtz free



energy, mean energy, and heat capacity of the system. Comment on the heat capacity relative to an ideal gas at constant volume.

24. The energy difference between the lowest atomic state  $1S_0$  and first excited  $3S_1$  state of the helium atom is  $159,843 \text{ cm}^{-1}$ . The superscripts of the spectroscopic states denote the degeneracy. Evaluate the fraction of excited states in He gas at 6000 K.
25. (a) Find the ratio of the number of ortho-hydrogen and para-hydrogen molecules in a  $H_2$  gas. What would this be for heavy hydrogen  $D_2$ ? The nuclear spin of H is  $1/2$  and of D is 1, and ortho has the greater spin weight than para.
- (b) The rate of ortho-para conversion is so small that the two forms can be separated as though they are different kinds of gases. Calculate the specific heat at low temperatures and show that para-hydrogen has the larger specific heat.
26. A crude estimate of the surface temperature of the earth is to assume that the clouds reflect a fraction of all sunlight, the rest being absorbed by the earth and reradiated. Treating the sun as blackbody at a temp  $T = 5800\text{K}$ , find the surface temp of the earth. You may assume the earth is an ideal absorber and that the rotation of the earth allows it to emit in all directions. The radius of the sun is  $6.96 \times 10^8 \text{ m}$  and that of the earth is  $6,400 \text{ km}$ . The mean distance between the sun and the earth is  $1.5 \times 10^8 \text{ m}$ .
27. A simplified model of diffusion consists of a one-dimensional lattice, with lattice spacing  $a$ , in which an "impurity" makes a random walk from one lattice site to an adjacent one, making jumps at time intervals  $\Delta t$ . After  $N$  jumps, the atom has taken  $N_1$  steps to the right and  $N_2$  steps to the left with  $N = N_1 + N_2$ . It is now located at  $x = a(N_1 - N_2)$ .
- a) Find the probability the atom is at  $x$ , after  $N$  steps, given  $N_1, N_2 \gg 1$ .
- b) If  $a, \Delta t$  are taken infinitesimal the probability in (a) satisfies the diffusion equation

$$\frac{\partial P}{\partial t} = D \frac{\partial^2 P}{\partial x^2}$$

Find an expression for  $D$  in the terms of  $a$ ,  $\Delta t$ .

28. Show that :  $C_p = C_V + TV\alpha^2 / \kappa_T$ , where  $C_p$  and  $C_V$  are the heat capacities at constant pressure and volume, respectively,  $\alpha = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_p$  is the coefficient of thermal expansion, and  $\kappa_T = -\frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_T$  is the isothermal compressibility.
29. Lead has a molar mass of 207.2 g/mole. At 25°C and 1 atmosphere of pressure, it has an isothermal bulk modulus of  $B = 1.6 \times 10^{10}$  Pa, a mass density  $\rho = 11.4$  g/cm<sup>3</sup>, and a coefficient of thermal expansion of  $87 \times 10^{-6}/^\circ\text{C}$ . Its specific heat at constant pressure  $C_p = 128$  J/kg-°C.
- How big is the difference between  $C_p$  and its constant volume specific heat  $C_V$ ?
  - The Law of Dulong and Petit states that the heat capacity of any solid at room temperature arises from the vibrations of the atoms (3N degrees of freedom), which can be calculated by treating the vibrations as a set of 3N classical harmonic oscillators. Does the Law of Dulong and Petit describe  $C_p$  or  $C_V$ ? What would you predict the heat capacity of lead to be if this law is correct?
  - Find the Debye temperature of lead. How does the specific heat of lead vary with temperature for temperatures well below the Debye temperature?
30. Consider a monoatomic ideal gas of mass density  $\rho$  at temperature  $T$ , whose atoms have mass  $m$ . The number of atoms with velocities  $\vec{v}$  in the velocity space volume element  $d^3\vec{v}$  is given by the Maxwell-Boltzmann distribution
- $$n(\vec{v})d^3\vec{v} = \frac{\rho}{m} \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp\left( \frac{-m(v_x^2 + v_y^2 + v_z^2)}{2mk_B T} \right) d^3\vec{v}$$
- What is the average velocity  $v_{avg}$ ?

- b) Derive the distribution of speed  $P(v)dv$ .
- c) What is the most probable speed  $v^*$ ?
- d) Obtain expressions for the average  $\bar{v}$ , and root-mean-square speed  $v_{rms}$  and  $v^*$ , and rank them increasing order.  
 [Hint:  $\int_0^\infty x^n e^{-x^2} dx = \frac{1}{2} \Gamma\left(\frac{n+1}{2}\right)$ .]
31. A certain material is completely specified by its volume  $V$  and temperature  $T$ . It has an equation of state  $p = AT^4$ , where  $A$  is a constant independent of the volume. The heat capacity at fixed volume is measured to be  $BVT^3$ .
- a) From dimensional analysis,  $B$  and  $A$  have the same units. Show that  $B = 12A$ .
- a) Find the entropy of this material as a function of  $V$  and  $T$ .
- c) If this material is cooled adiabatically and reversibly from 20K to 10K, by how much does the volume change?
32. Consider an ideal Fermi gas of spin 1/2 particles in 3-dimensional box. The number of particles per unit volume is  $n$ , the mass of the particles is  $m$ , and the energy of the particles is the usual  $E = p^2/2m$ . Assume that the temperature is quite low.
- a) Find formulas for the Fermi energy  $E_F$ , Fermi wavevector  $k_F$ , and Fermi temperature  $T_F$  in term of  $m$ ,  $n$  and constants such as  $h$  and  $k_B$ .
- b) Find the total energy of the gas at zero temperature.
- c) Show that the heat capacity at low temperature is proportional to  $T$ .
33. A collection of  $N$  spin 1/2 atoms are fixed in a solid. The atoms do not interact with each other. The magnetic moment of each atom is  $\pm\mu_0$ . If a magnetic field  $H$  is applied to the solid, each atom has an energy of  $\pm\mu_0 H$ .
- a) Find the mean energy  $\langle E \rangle$  in a magnetic field at a given temperature  $T$ .

- b) Find the entropy of this collection.
- c) The magnetization  $m$  of a solid is defined as the net magnetic moment per unit volume. The average magnetic moment is defined via  $\langle E \rangle = - \langle M \rangle H$ . For noninteracting moments, the magnetization typically obeys a Curie Law where  $m = \chi_0 H/T$  for vanishingly small  $H$ . Find the value of the constant  $\chi_0$  for this problem.
34. In the early universe, a chemical equilibrium between photons and  $e^+$ ,  $e^-$  particles was achieved via the conversion process
- $$e^+ e^- \leftrightarrow 2\gamma.$$
- The energy of an electron or a positron is given by  $E = mc^2 + (1/2) mv^2$ . Using the fact that photon have zero chemical potential, derive an equation describing the concentrations  $n^+$  and  $n^-$  of positrons and electrons are related to each other at a given temperature.
35. A collection of  $N$  bosons is contained in a volume  $V$ . The spin of the particles is 0.
- a) Find the temperature at which Bose condensation occurs.
- b) Find how the number of particles in the lowest energy state varies with temperature below the condensation temperature.
36. The average energy of a system in thermal equilibrium is  $\langle E \rangle$ . Prove that the mean square deviation of the energy,  $\langle (E - \langle E \rangle)^2 \rangle$  is given by

$$\langle (E - \langle E \rangle)^2 \rangle = k_B T C_V,$$

where  $C_V$  is the heat capacity of the system at constant volume and  $k_B$  is the Boltzmann constant. Use this result to show that the energy of a macroscopic system may ordinarily be considered constant when the system is in thermal equilibrium.

37. Consider a container of volume  $100 \text{ cm}^3$  containing a classical ideal gas at 1 atm pressure and 350K.
- Find the number of particles.
  - Compute the mean kinetic energy of a particle in the gas.
  - Suppose one counted the number of particles in a small subvolume of size 0.1 micron on a side. What is the probability of finding no particles in this volume?
38. The pressure in a vacuum system is  $10^{-3} \text{ mm Hg}$ . The external pressure is 1 atm at 300 K. This is a pinhole in the vacuum system of area  $10^{-10} \text{ cm}^2$ . Assume that any molecule entering the pinhole goes through. Use an average molecular weight of air as 29 amu.
- How many molecules enter the vacuum system each hour?
  - If the volume of the system is 2 liters, by how much does the pressure rise in 1 hour?
  - How long does it take for the pressure to rise to 750 mm Hg? Note: this is close to the pressure outside the vacuum tank.
39. The diatomic molecule HD has a set of rotational energy levels  $E_\ell = k_B \theta_r \ell(\ell+1)$  which are  $(2\ell+1)$  degenerate, and a vibrational spectrum  $E_v = (k_B \theta_v)(n_v + \frac{1}{2})$ .  $\theta_r$  is called the rotational temperature, and  $\theta_v$  the vibrational temperature.
- Assuming the molecules do not interact among themselves, evaluate the partition sum for  $N$  atoms confined to a volume  $V$ . You may not be able to compute all the sums in closed form.
  - Evaluate the Helmholtz Free energy  $F(T, V, N)$  in the limits  $T \ll \theta_r, \theta_v \ll T \ll \theta_v$ , and  $T \gg \theta_v$ . It will help to use the fact that when  $k_B T$  is much smaller than the spacing of the energy levels, the sum can be computed as an integral.
  - Sketch, as accurately as you can, the behavior of  $C_v(T)$  from 25K to 5000K, using a logarithmic scale in temperature. Assume that  $\theta_r = 100\text{K}$  and  $\theta_v = 3000\text{K}$ .

40. Consider an equilibrium gas consisting of two types of atoms of masses  $m_1$  and  $m_2$ , both obeying Maxwellian velocity distribution corresponding to the same temperature  $T$ ,

$$f_i(\vec{v}_i)d\vec{v}_i = \left(\frac{m_i}{2\pi kT}\right)^{3/2} \exp[-m_i v_i^2 / 2kT] d\vec{v}_i,$$

where  $m_i$  is the mass of particle type  $i$ , and the  $f_i$  are the corresponding velocity distributions. Using the well-known identity

$$m_1 \vec{v}_1^2 + m_2 \vec{v}_2^2 = (m_1 + m_2) \vec{V}^2 + \mu \vec{v}^2,$$

where  $\vec{V}$  is the center-of-mass velocity,  $\vec{v}$  is the relative velocity and  $\mu = m_1 m_2 / (m_1 + m_2)$  is the reduced mass, show that the distribution of relative velocities between the two types of atom is also Maxwellian, with distribution

$$f_{1,2}(\vec{v})d\vec{v} = \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp[-\mu v^2 / 2kT] d\vec{v}.$$

41. An object of heat capacity  $C$  is used as the cold thermal reservoir by a Carnot engine. The hot reservoir has an infinite heat capacity. During the operation of the engine to produce work, the temperature of the cold reservoir will slowly rise. Assume the starting temperature of the cold reservoir is  $T_c$  and the constant temperature of the hot reservoir is  $T_h$ .

- To what temperature will the cold reservoir rise before the engine ceases to produce work?
- How much heat flows into the cold reservoir until the engine stops producing work?
- What is the total amount of work the engine can produce before the process stops?

42. A certain gas has an equation of state

$$P = b + \frac{nRT}{V}.$$

- a) Find the value of  $C_p - C_v$ , where  $C_p$  and  $C_v$  are the heat capabilities at fixed pressure and volume.
- b) Show that the constant volume heat capacity is not dependent on the volume. Specify how the heat capacity can depend on  $n$  and  $T$ .
- c) This gas undergoes a process at fixed temperature where the volume is changed from  $V_i$  to  $V_f$ . Find the change in entropy in terms of the variables  $n$ ,  $R$ ,  $T$ ,  $V_f$  and  $V_i$ .
43. Consider a classical gas composed of  $N$  particles of mass  $m$  that possess a permanent electric dipole moment  $p$ . The gas is subject to a uniform electric field of size  $E$  in the  $x$ -direction and is enclosed in a container of size  $V$ . The potential energy of a dipole is  $-\vec{E} \cdot \vec{p}$ .
- a) Find the partition function.
- b) Find the net polarization of the sample as a function of field strength, pressure, and temperature. The polarization  $P$  is defined as the net dipole moment per unit volume.
44. The energy spectrum of neutrinos (spin  $1/2$  massless particles) is  $E=pc$ . For a collection of  $N$  neutrinos confined to volume  $V$ , calculate
- a) The Fermi wave vector.
- b) The Fermi energy.
- c) The total energy at  $T = 0$ .
- d) The compressibility of the neutrino gas.
45. Consider an ideal Fermi gas of spin  $-1/2$  particles in a 3-dimensional box. The number of particles per unit volume is  $n$ , the mass of the particles is  $m$ , and the energy of the particles is the usual  $E=p^2/2m$ . Assume that the temperature is quite low.

- a) Find formulas for the Fermi energy  $E_F$ , Fermi wavevector  $k_F$ , and Fermi temperature  $T_F$  in terms of  $m$ ,  $n$  and constants such as  $h$  and  $k_B$ .
- b) Find the total energy of the gas at zero temperature.
- c) If the magnetic moment of the particles is  $\mu_e$ , show that the paramagnetic susceptibility  $\chi$  for low fields in the limit of zero temperature is given by

$$\chi = \frac{3n\mu_e^2}{2E_F}$$

46. Consider a system consisting of two particles, each of which can be in any one of three quantum states of respective energies  $0$ ,  $\epsilon$ , and  $3\epsilon$ . The system is in contact with a heat reservoir at temperature  $T$ .

- a) Write an expression for the partition function  $Z$  if the particles obey classical Maxwell-Boltzmann statistics and are considered distinguishable.
- b) Write a similar expression if the particles obey Bose-Einstein statistics.
- c) Write a similar expression if the particles obey Fermi-Dirac statistics.

47. A box of volume  $V$  hold blackbody radiation at a temperature  $T$ .

- a) Show that the amount of energy stored in a small range of frequencies  $(f, f + df)$  is given by

$$E_f df = \frac{3af^3}{e^{bf} - 1} df ,$$

and find all expressions for  $a$  and  $b$  in terms of  $V$ ,  $T$ ,  $K_B$ ,  $h$ ,  $c$ .

- b) The Wien displacement law describes the relationship between the peak intensity in the blackbody energy distribution (1) and the temperature. Derive this relationship. Note: the function  $x^3/(e^x - 1)$  has a maximum at  $x = 2.82$  approximately.
- c) Find the total energy of the blackbody radiation and how it depends on  $V$ ,  $T$ ,  $h$ ,  $c$ ,  $k_B$ .



48. Consider a degenerate electron gas in which all electrons are considered to be highly relativistic, so that their energy  $\epsilon = cp$  with  $p$  the magnitude of the momentum vector.
- Calculate the density of states for this system.
  - Derive a relation, at zero temperature, between the particle density  $N/V$  and the Fermi energy  $\epsilon_F$  for this system.
  - The internal energy of a nonrelativistic zero temperature 3D electron gas satisfies  $U = \frac{3}{5} N\epsilon_F$ . Derive the corresponding relation for the present relativistic electron gas.

49. According to quantum mechanics the possible energy levels of a simple harmonic oscillator are given by

$$E_n = (n + \frac{1}{2})\hbar\omega ,$$

where  $n=0, 1, 2, 3, \dots$ ,  $\hbar$  is the Planck's constant (divided by  $2\pi$ ), and  $\omega$  is the angular frequency of the oscillation.

- Calculate the average energy of the oscillator at a fixed temperature  $T$ .
  - The Einstein solid consists of  $3N$  such harmonic oscillators, all at the same frequency  $\omega$ . Find the heat capacity at constant volume of the Einstein solid and describe its behavior at high temperature and low temperature limits, respectively.
50. Derive the density of states for a uniform gas of bosons confined to an area  $A$  in two spatial dimensions. Show that Bose-Einstein condensation is not possible for this system. Finally, determine the system chemical potential, as a function of temperature and sketch it.
51. An interesting thermometer may be made by observing the voltage fluctuations in a circuit consisting of an ideal inductor  $L$  connected in parallel to an ideal capacitor  $C$ . The circuit is in thermal contact with a heat reservoir at temperature  $T$ .

- (a) Write down an expression for the electric energy stored in the capacitor  $C$  and magnetic energy stored in the inductor  $L$ . Show that this system is a harmonic oscillator with appropriate analogs of mass and spring constant. What is the natural frequency  $\omega_0$  of this oscillator?
- (b) Using classical statistical mechanics, deduce the root-mean-square voltage in the circuit  $V_{\text{rms}} = \sqrt{\langle V^2 \rangle}$ .
- (c) Assuming that the oscillator energy states follow the quantum mechanical rule  $E_n = \hbar\omega_0 \left( n + \frac{1}{2} \right)$ , where  $\omega_0$  is the classical frequency of the oscillator,  $\hbar$  is the Planck constant, and  $n = 0, 1, 2, \dots$ , deduce the temperature dependence of  $V_{\text{rms}}$ .
- (d) Sketch  $V_{\text{rms}}^2$  vs.  $T$ . Evaluate the low and high  $T$  behavior of  $V_{\text{rms}}^2$  and compare with the classical result. For what range of  $T$  would this thermometer be useful?

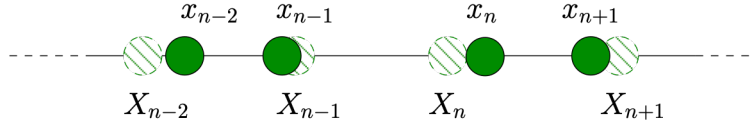
52. A monoenergetic beam of neutrons passes through a slab of Pb. For simplicity consider scattering of neutrons by Pb nuclei only in the two-dimensional plane. Each neutron is deflected left or right by a small angle,  $\pm \theta_0$ , with equal probability after a collision with a Pb nucleus. Assume  $\theta_0 \ll 1$  and that the neutrons behave as classical particles moving at constant speed between collisions. Let  $\tau$  be the time between successive collisions with nuclei that are separated by the atomic lattice spacing  $a$ .

- (a) What is the probability that a neutron will be deflected by angle  $\theta(t)$  after time  $t = n\tau$ , i.e. after  $n > 1$  successive collisions? Assume each collision is independent of the past history. Show that the probability distribution for  $\theta(t)$  is normalized.
- (b) Calculate the mean angular displacement,  $\langle \theta(t) \rangle$ , of a beam of neutrons assuming each neutron traverses the target and encounters  $n$  nuclei in time  $t$ .
- (c) Show that the mean square angular displacement of a beam of neutrons obeys the equation,  $\langle \theta(t)^2 \rangle = D t^\gamma$ , for  $t > \tau$ . Calculate the exponent  $\gamma$  and the coefficient  $D$  in terms of the microscopic parameters:  $\theta_0$ ,  $\tau$ , and  $a$ .

Tip: You may find the binomial expansion useful:

$$(a + b)^n = \sum_{p=0}^n \frac{n!}{p! (n-p)!} a^p b^{(n-p)}.$$

53. A small mirror of moment of inertia  $I$  is suspended from a quartz fiber which has an elastic torsion constant  $\tau$ . The mirror is in equilibrium with a gas of molecules at absolute temperature  $T$ . The mirror reflects a beam of light onto a distant screen such that the angular deflection,  $\theta$ , caused by collisions with surrounding molecules can be detected. The mean deflection of the mirror is  $\langle \theta \rangle = 0$ .
- (a) Starting from the appropriate partition function derive the probability density for the angular deflection of the mirror to be in the range  $(\theta, \theta + d\theta)$  when the mirror is in equilibrium with the gas at temperature  $T$ . Treat the motion of the mirror classically. You may assume that any particular angular deflection satisfies  $\theta \ll 1$ .
- (b) Calculate the mean square deflection,  $\langle \theta^2 \rangle$ , of the mirror at temperature  $T$  in terms of  $I$ ,  $\tau$ ,  $T$  and Boltzmann's constant,  $k_B$ .
- (c) Measurements at  $T = 300$  K give  $\langle \theta^2 \rangle = 1.01 \times 10^{-5}$ ,  $I = 1.1 \times 10^{-2}$  g-cm<sup>2</sup>, and  $\tau = 4.15 \times 10^{-9}$  dyne-cm. Note that the gas constant is  $R = 8.31 \times 10^7$  erg/mole-K, and all angles are in radians. From this data determine Avogadro's constant,  $N_A$ , i.e. the number of molecules per mole of gas.
- (d) Estimate the temperature below which the fluctuations of the mirror must be treated quantum mechanically.
54. Consider a one-dimensional solid with  $N$  atoms of mass  $M$  bound by a Hooke's law force to lattice sites  $X_n = n a$  where  $a$  is the separation between the atoms (Figure 3). The length of the chain of atoms is  $L = Na$ .



**Figure 3:** One-dimensional chain of atoms with masses  $M$ . The position of the atom bound to site  $X_n$  is  $x_n$ .

The Hamiltonian for the vibrations of the atoms about their equilibrium positions is

$$H = \sum_{n=1}^N \left[ \frac{p_n^2}{2M} + \frac{1}{2}K(x_n - X_n)^2 \right],$$

where  $K > 0$  is the Hooke's law constant, and  $p_n$  and  $x_n$  are the canonically conjugate momentum and displacement operators for the atom located near site  $X_n$ .

- (a) Express the Hamiltonian in terms of the number operator for quantized vibrations of the atoms about their equilibrium positions.
- (b) The solid is in equilibrium with a heat bath at absolute temperature  $T$ . Calculate the mean number of vibrational quanta for each atom in thermal equilibrium.
- (c) Identify the characteristic temperature,  $\Theta_E$ , separating the high temperature classical limit from the low temperature quantum limit for the mean number of vibrational quanta. Express  $\Theta_E$  in terms of Planck's constant,  $\hbar$ , Boltzmann's constant,  $k_B$ , and the properties of the atomic solid,  $M$ ,  $K$ ,  $a$ .
- (d) Obtain a general formula for the temperature dependence of the heat capacity at constant length,  $C_L(T)$ . Express the result in terms of  $N$ ,  $T$ ,  $\Theta_E$  and fundamental constants. Calculate the leading order expressions for  $C_L(T)$  in the classical ( $T \gg \Theta_E$ ) and quantum ( $T \ll \Theta_E$ ) limits.
- (e) Calculate the root-mean-square (*rms*) displacement of an atom from its equilibrium position. Assuming the solid melts when the *rms* displacement is a fraction  $f < 1$  of the lattice spacing  $a$ , calculate the melting temperature  $T_M$  assuming the solid is stable in the classical limit.

55. Quantization of the vibrational motion of the atoms of a solid leads to a Hamiltonian for independent modes of vibrational quanta (phonons),  $H = \sum_{\mathbf{k}\lambda} \hbar\omega_{\mathbf{k}\lambda} a_{\mathbf{k}\lambda}^\dagger a_{\mathbf{k}\lambda}$ , where  $a_{\mathbf{k}\lambda}^\dagger$  ( $a_{\mathbf{k}\lambda}$ ) creates (destroys) a phonon of wavevector  $\mathbf{k}$  and polarization  $\lambda$ , and  $\hbar\omega_{\mathbf{k}\lambda}$  is the quantum of energy of the phonon. Like photons, phonons obey Bose-Einstein statistics and are massless with  $\omega_{\mathbf{k}\lambda} = c_\lambda |\mathbf{k}|$ , where  $c_\lambda$  are the velocities of polarized phonons. Unlike photons, there are three polarized phonons - two transverse and one longitudinal phonon for each  $\mathbf{k}$ . For simplicity assume the same velocity for all three polarized branches of phonons, i.e.  $c_\lambda = c$ .

For a solid of volume  $V$  containing  $N$  atoms there are 3 vibrational degrees of freedom per atom, and thus  $3N$  modes of vibration. The total number of modes determines the maximum wavenumber (shortest wavelength),  $k_D$ , and thus a maximum phonon frequency,  $\Omega_D = c k_D$ , of a phonon. The latter also defines the Debye temperature,  $\Theta_D$ , below which the Bose-Einstein statistics of the phonons becomes important.

- (a) Express  $\Theta_D$  in terms of  $N/V$ ,  $c$  and fundamental constants. Calculate the phonon density of modes,  $\mathcal{D}(\omega)$ , i.e. the number of phonon modes per unit frequency in the range  $(\omega, \omega + d\omega)$ . Express the result in terms of  $N$ ,  $\omega$  and  $\Omega_D$ .
- (b) Show that the internal energy can be expressed as  $E(T) = N k_B T f(T/\Theta_D)$ . Obtain an integral representation for the function  $f(x)$ .
- (c) Calculate the phonon specific heat at constant volume for  $T \gg \Theta_D$  and for  $T \ll \Theta_D$ .

56. The Ising model of interacting atomic spins exhibits a thermodynamic phase transition between a thermally disordered paramagnetic (PM) phase and an ordered ferromagnetic (FM) phase. The internal energy is

$$E = -\frac{1}{2} \sum_{i \neq j} J_{ij} s_i s_j,$$

where the  $N$  atoms are located at lattice sites labelled by  $i = 1, 2, \dots, N$ . Each atom has a spin variable that can take only two possible values,  $s_i = \pm 1$ . The interaction energy between a spin at site  $i$  and another at site  $j$  is given by  $J_{ij}$ . If  $J_{ij} > 0$  the interaction favors ferromagnetic alignment of the two

spins otherwise anti-ferromagnetic alignment. Consider the “infinite range” Ising model, in which every spin interacts with every other spin, with strength  $J/N$ ,

$$E = -\frac{1}{2} \frac{J}{N} \sum_{i,j} s_i s_j,$$

where the double sum is now over all possible pairs of spins on a lattice of  $N$  spins. Consider the case  $J > 0$  favoring ferromagnetic alignment of the spins. The magnetization  $M = \sum_i s_i$  is an extensive thermodynamic variable, as is the internal energy and entropy. The intensive variables are: the polarization of the system of spins,  $m = M/N$ , the energy per atom,  $\varepsilon = E/N$  and the entropy per atom,  $\mathcal{S} = S/N$ . The Boltzmann entropy for a macrostate is  $S = k_B \ln W$ , where  $W$  is the number of microstates that give the same macrostate. The allowed values of the polarization are  $-1 \leq m \leq +1$ , with  $m = +1$  corresponding to all spins “up”,  $m = -1$  to all spins “down” and  $m = 0$  to a PM phase.

- (a) Calculate the energy per atom for a macrostate with polarization,  $m$ .
- (b) Consider configurations of the  $N$  spins, with  $n$  “up” spins and  $N - n$  “down” spins. Each possible configuration has polarization,  $m = 2p - 1$ , with  $p = n/N$ . How many possible configurations are there of  $N$  spins, with  $n$  “up” and  $N - n$  “down”? Calculate the entropy per atom,  $\mathcal{S}(m)$ , for a macrostate with polarization  $m$ . Use Stirling’s approximation to evaluate logarithm’s of factorials of large numbers,  $\ln n! \approx n \ln(n) - n$  for  $n \gg 1$ .
- (c) Consider the Helmholtz free energy per atom,  $f = \varepsilon - T\mathcal{S}$ . Show that the FM state is the equilibrium state at sufficiently low temperature, while the PM state is thermodynamically stable at sufficiently high temperature. Calculate the transition temperature  $T_c$  below which the FM phase is thermodynamically stable. Hint: The transition is second order, so expand the free energy in powers of  $m$  for  $|m| \ll 1$ .
- (d) Find the equilibrium value of  $m(T)$  for  $(T_c - T) \ll T_c$  and show that the spontaneous magnetization varies with temperature as,  $m(T) \sim (T_c - T)^\beta$  for  $T \rightarrow T_c^-$ , and determine the exponent  $\beta$ .

57. At temperatures comparable to the rest mass energy of the electron,  $mc^2$ ,

particle collisions lead to the creation of electron-positron pairs. As such the number of particles is no longer conserved. The production of an  $e^+e^-$  pair, and the reverse process (annihilation) establish chemical equilibrium with photons ( $\gamma$ ):  $e^+ + e^- \longleftrightarrow \gamma$ .

- (a) What is the thermodynamic condition for equilibrium between electrons, positrons and photons?
- (b) Estimate the temperature in Kelvin at which  $e^+e^-$  pair creation becomes dominant.
- (c) Assuming equal numbers of electrons and positrons obtain a formula for the mean number of electrons and positrons in thermal equilibrium at temperature  $T$ . Give explicit results for the temperature dependence of the number density of electrons and positrons for (i)  $k_B T \ll mc^2$  and (ii)  $k_B T \gg mc^2$ . Express your result in terms of  $T$ ,  $m$ , and fundamental constants.
- (d) Calculate the energy densities of electrons, positrons and photons in the limit  $k_B T \gg mc^2$ . Express your result in terms of  $T$ ,  $m$ , and fundamental constants.